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Causative impact of air pollution on evapotranspiration in the North China Plain

Ling Yao[a,b,*]

[a] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing Normal University, Nanjing 210023, China

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ABSTRACT

Atmospheric dispersion conditions strongly impact air pollution under identical surface emissions. The degree of air pollution in the Jing-Jin-Ji region is so severe that it may impose feedback on local climate. Reference evapotranspiration (ET_0) plays a significant role in the estimation of crop water requirements, as well as in studies on climate variation and change. Since the traditional correlation analysis cannot capture the causality, we apply the convergent cross mapping method (CCM) in this study to observationally investigate whether the air pollution impacts ET_0. The results indicate that southwest regions of Jing-Jin-Ji always suffer higher $PM_{2.5}$ concentration than north regions through the whole year, and correlation analysis suggests that $PM_{2.5}$ concentration has a significant negative effect on ET_0 in most cities. The causality detection with CCM quantitatively demonstrates the significantly causative influence of $PM_{2.5}$ concentration on ET_0, higher $PM_{2.5}$ concentration decreasing ET_0. However, CCM analysis suggests that $PM_{2.5}$ concentration has a relatively weak causal influence on ET_0 while the correlation analysis gives the near zero correlation coefficient in Zhangjiakou city, indicating that the causative influence of $PM_{2.5}$ concentration on ET_0 is better revealed with CCM method than the correlation analysis. Considering that ET_0 is strongly associated with crop water requirement, the amount of water for agricultural irrigation could be reduced at high $PM_{2.5}$ concentrations. These findings can be utilized to improve the efficiency of water resources utilization, and reduce the exploiting amount of groundwater in the Jing-Jin-Ji region, although $PM_{2.5}$ is detrimental to human health.

1. Introduction

In recent years, serious air pollution, especially $PM_{2.5}$ pollution in Eastern China has attracted widespread attention due to its relationship to all-cause and specific-cause mortality (Qiao et al., 2014; Pascal et al., 2014; Lanzinger et al., 2016; Chen et al., 2017). Chan and Yao (Chan and Yao, 2008) indicates that the Jing-Jin-Ji (JJJ) region, located in the north of the North China Plain (NCP), has been undergoing severe air pollution, and smog events have occurred frequently in this region since 2012, with the highest annual level of fine particulate matter concentration exceeded 690 μg/m^3 (Xu et al., 2015). A lot of researches have been conducted for investigation of source apportionment, physical characteristics, chemical composition and seasonal variations based on $PM_{2.5}$ ground observations and remote sensing retrievals (Cao et al., 2014a; Liu et al., 2014; Han et al., 2015; Hu et al., 2015; Wang et al., 2015a; Yang and Christakos, 2015; Sicard et al., 2016). At the same time, some studies (Zhang et al., 2015; Chen et al., 2016; Pearce et al., 2011; Galindo and Varea, 2011; Cao et al., 2014b; Wang et al., 2015b) have made analysis of the relationships between meteorological parameters (wind direction, wind speed, temperature and relative humidity) and air pollutants, indicating that the variation of synoptic patterns strongly modulated pollutant concentrations. As a matter of fact, both spatial and temporal scales of air pollution happening in the NCP is comparable to synoptic processes and thus it is possible for air pollution to impact the climate in this region. However, little attention is paid to whether or not serious air pollution imposes feedback on regional climatic variables, such as precipitation and temperature except Chen's investigation. They demonstrate that $PM_{2.5}$ pollution has an effect on average relative humidity and minimum temperature (Chen et al., 2017).

The NCP, including JJJ, has also been confronting the serious problem of water resources scarcity. It is well known that the NCP, including JJJ, is one of the most important agricultural production areas in China. Currently, the Plain has 17,950 thousand ha of cultivated

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[*] Correspondence address: State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
E-mail address: yaoling@lreis.ac.cn.

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land, 71.1% of which is irrigated, consuming more than 70% of the total water supply (Wang et al., 2014; Liu et al., 2001). The sequential growth of winter wheat and summer corn in one year is the main cropping rotation system there. The irrigation for this agriculture production consumes water greatly due to evapotranspiration from both soil and crop. The precipitation cannot meet the need for water, and thus groundwater has been extracted intensively, leading to an urgent threat to the ecosystem and the sustainable development of agriculture.

Reference evapotranspiration (ET_0) plays a significant role in the estimation of crop water requirements and irrigation scheduling, irrigation and drainage design, assessing groundwater recharge, predicting crop yield, and planning land use (Zhan and Feng, 2003). So, its spatiotemporal variation has attracted much attention under the background of climate change (Bandyopadhyay et al., 2012). As mentioned above, the serious air pollution suffered by the NCP has been impacting the local climatic variables, based on which ET_0 is calculated. So, ET_0 is the most likely to be affected by the air pollution in turn. However, to the author's knowledge, no research has been conducted on this topic although ET_0 is very significant for making regional crop irrigation water-saving system, adjusting the dynamic distribution of crops, and improving regional ecological environment in water shortage regions.

In this study, we will quantitatively evaluate whether or not the air pollution impact ET_0 in the JJJ region. Firstly, cross correlations between regional $PM_{2.5}$ concentration and ET_0 are examined after analyzing spatiotemporal patterns of $PM_{2.5}$ concentration. Secondly, the convergent cross mapping (CCM) method is further applied to quantify the causative influence of $PM_{2.5}$ concentration on ET_0 because the correlation does not mean causation. It is hoped that these analysis can provide a useful reference for improving the utilization of agricultural water resources and developing water-saving agriculture.

2. Materials and methods

2.1. Study region

The Jing-Jin-Ji (JJJ) region, located in the north of the NCP, has a special socioeconomic status in China. The JJJ consists of two megacities (Beijing and Tianjin) and Heibei province. Hebei comprises 11 cities, including Shijiazhuang, Cangzhou, Baoding, Tangshan, Zhangjiakou, Chengde, Qinhuangdao, Hengshui, Xingtai, Langfang, and Handan. Eight cities in this region rank in the top10 list of cities with the worst air quality in 2014 (Li et al., 2017). Local governments deploy an air quality monitoring network containing 79 stations to get a better understanding of airborne pollutants and provide air pollution warning for local residents. In this region, the China Meteorology Administration deploys weather stations to collect meteorological variables (Fig. 1).

2.2. Data sources

In this study, one year of station $PM_{2.5}$ and meteorological data is used for analysis from March 2015 to February 2016. The real-time hourly observations of $PM_{2.5}$ concentration for all monitoring cities are released by China National Environmental Monitoring Center (CNEMC) (http://113.108.142.147:20035/emcpublish/). The daily $PM_{2.5}$ concentration for each city is calculated by averaging hourly $PM_{2.5}$ concentration observations at all available monitoring stations. The data monitoring techniques have been described in the previous research (Yao et al., 2015). The 12 months are divided into following seasonal categories: spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February).

Daily meteorological data for each city are obtained from China Meteorological Data Service Center (CMDC) (http://data.cma.cn/). In the JJJ region, there are a total of 25 weather stations (Fig. 1). At these stations, eight meteorological elements can be obtained, including mean pressure, mean temperature, mean water vapour, mean relative humidity, mean wind speed, evaporation, sunshine duration and precipitation. It is noted that there is no weather station at Handan city despite the existence of a pollutant monitoring station and thus the causality analysis is not conducted here.

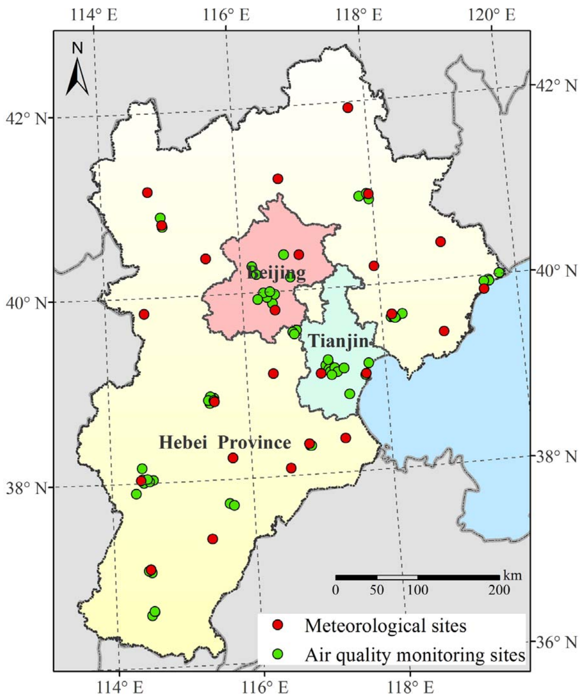

Fig. 1. Geographical locations of these cities and ground observation stations of $PM_{2.5}$ concentration and meteorological parameters. Green points represent $PM_{2.5}$ monitoring sites, and red points stand for meteorological monitoring stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Methods

2.3.1. Estimation of reference evapotranspiration estimation

The Food and Agriculture Organization (FAO) Penman-Monteith (PM-ET_0) equation proposed by Allen et al. (1998) for daily ET_0 computation takes the form:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is the grass reference evapotranspiration [mm day^{-1}], R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2-meter height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapour pressure [kPa], e_a is actual vapour pressure [kPa], e_s-e_a is saturation vapour pressure deficit [kPa], Δ is slope of the vapour pressure curve [kPa $°C^{-1}$], and γ is psychometric constant [kPa $°C^{-1}$].

As well known, many meteorological variables required by Eq. (1) are not measured at many weather stations, such as net radiation and ground heat flux, and have to be estimated according to other variables, causing unignorable uncertainties to the final estimates. Hence, many more practical schemes, such as the empirical Hargreaves-Samani (HS) equation and Penman-Monteith temperature (PMT) method (Todorovic et al., 2013; Hargreaves and Samani, 1985; Annandale et al., 2002), are established for estimation of ET_0. In this study, a concise algorithm is taken for calculation of ET_0:

$$ET_0 = 0.0135k_{Rs}\frac{R_a}{\lambda}\sqrt{(T_{max} - T_{min})}(T + 17.8) \tag{2}$$

where 0.0135 is the ratio between the empirical coefficient 0.0023 to